ARMY RESEARCH LABORATORY

High Performance Visors

by Peter G. Dehmer and Melissa A. Klusewitz

ARL-RP-45 August 2002

A reprint from the 8th Department of Defense Electromagnetic Windows Symposium,
U.S. Air Force Academy, Colorado Springs, CO, April 2000.

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Abstract

Polycarbonate (PC) has been the material of choice for both military and commercial eye protection since its introduction nearly 40 years ago. PC is a clear, easily molded material with excellent impact resistance over a broad temperature range. It does, however, have several limitations; its impact properties are degraded by extended exposure to direct sunlight, it is attacked by common solvents, and its impact performance does not scale with thickness. This paper discusses the development of materials for two new visors, an all-plastic riot visor to replace an existing PC item and a glass/plastic visor to replace the existing acrylic/PC explosive ordnance disposal (EOD) visor. The goal for the riot visor is to improve the ballistic performance by 30% while maintaining or reducing the overall weight of the visor. The goal for the EOD visor is to produce an item that provides protection equal to that of the standard issue helmet while reducing the weight of the visor 30%, compared to the existing EOD visor. The approach is to investigate polyurethane (PU) materials for use in the all-plastic riot visor and to investigate the use of glass/plastic or plastic/plastic laminates using the PU materials to reduce the weight and increase the performance of the EOD visor. Issues addressed will include materials selection, bonding and fabrication, and ballistics evaluation. The results of this effort are the ballistic characterization of the PU materials for use in both all plastic and glass/plastic systems.

High Performance Visors

P.G. Dehmer* and M. A. Klusewitz*

Polycarbonate (PC) has been the material of choice for both military and commercial eye protection since its introduction nearly 40 years ago. PC is a clear, easily molded material with excellent impact resistance over a broad temperature range. It does, however, have several limitations; its impact properties are degraded by extended exposure to direct sunlight, it is attacked by common solvents, and its impact performance does not scale with thickness. This paper discusses the development of materials for two new visors, an all-plastic riot visor to replace an existing PC item and a glass/plastic visor to replace the existing acrylic/PC explosive ordnance disposal (EOD) visor. The goal for the riot visor is to improve the ballistic performance by 30% while maintaining or reducing the overall weight of the visor. The goal for the EOD visor is to produce an item that provides protection equal to that of the standard issue helmet while reducing the weight of the visor 30%, compared to the existing EOD visor. The approach is to investigate polyurethane (PU) materials for use in the all-plastic riot visor and to investigate the use of glass/plastic or plastic/plastic laminates using the PU materials to reduce the weight and increase the performance of the EOD visor. Issues addressed will include materials selection, bonding and fabrication, and ballistics evaluation. The results of this effort are the ballistic characterization of the PU materials for use in both all plastic and glass/plastic systems.

INTRODUCTION

Polycarbonate (PC) has been the material of choice for both military and commercial eye protection since its introduction nearly 40 years ago. PC is an easily formed or molded thermoplastic material that has been used by the U. S. Army for aircrew visors and sun, wind, and dust (SWD) goggles since the early 1970s[1] and spectacles since the mid 1980s.[2] This equipment provides protection from small (1 gram or less), slow moving (650 ft/sec) fragments but, does not provide full-face coverage. Although PC provides adequate protection from these fragment threats, several investigations have been undertaken to develop new materials and systems for

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improved ballistic protection.[3,4] These efforts uncovered several candidate materials including polyurethane (PU), transparent nylons, and glass/plastic laminates. Although these materials showed promise, either the increase in performance was not sufficient to warrant further investigation or the material had some shortcoming such as excessive color, high cost, or lack of a commercial source, which disqualified it from further consideration.

The goal for this effort is to provide the soldier with increased full-face protection from small fragments, not bullets. This is accomplished by improving the performance of two existing visors. The first is a riot visor (Fig. 1). This full-face, helmet-mounted visor is injection molded from clear PC, is approximately 0.250-in thick, and is required to protect the user from large, low-velocity projectiles, such as rocks and bottles, and from small higher velocity fragments. Through the use of a new PU material, the ballistic performance of this visor was improved by 30% with a slight reduction in the visor's weight. The second, an explosive ordnance disposal (EOD) visor (Fig. 2) a full-face helmet mounted visor, is a laminated structure with a 0.375-in thick acrylic outer ply and a 0.25-in thick PC inner ply. This visor is designed to provide protection from small, very high velocity (2000 ft/sec) fragments encountered by mine and ordinance disposal personnel. Through the use of glass/plastic laminates, the weight of this visor was reduced 30%, with no loss of performance.

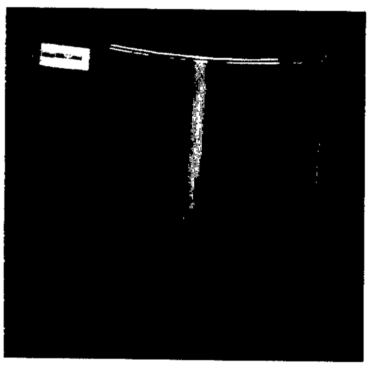

Fig. 1 Riot Visor

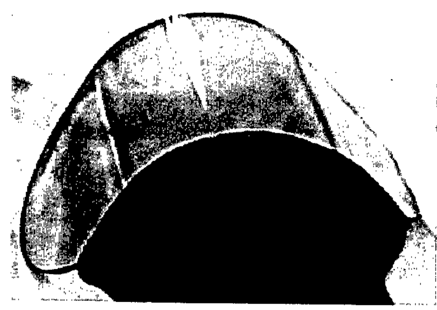

Fig. 2 S820 EOD Visor

APPROACH

The approach was to investigate PU materials for use in the all-plastic riot visor and to investigate the use of glass/plastic or plastic/plastic laminates using the PU materials to reduce the weight and increase the performance of the EOD visor. The specifications for the riot and EOD visors are shown in Table 1.

Specifically, several thicknesses of PU were evaluated ballistically against a .22-caliber fragment simulator projectile (FSP) and compared to PC over the same thickness range. Baseline soda lime glass/PC laminates were fabricated and tested against the fragment threat. Using the same construction, Vycor/PC, Vycor/PU, fused silica/PC, fused silica/PU, Transarm/PU, and several all-plastic laminates were made and evaluated.

The results were then compared. The construction of several of the more promising candidate laminates was optimized.

Table 1
EXISTING VISOR SPECIFICATIONS

	V50 velocity w/ 17 grain ft/sec, m/sec	Approximate Areal Density lb/ft^2	Construction out to in inches
Army/ PS820	2050 /625 (QA)	4.27	0.375 Acrylic/ 0.25 PC
Riot Visor	850/259	1.55	0.250

MATERIALS

Plastics

Two types of plastics were investigated:

1. PC: This material was used as the baseline material for both monolithic and laminated systems because of its long-term use and acceptance by the armor community. The PC used was Lexan[+] 9034 stock purchased from a local distributor in 4-ft × 8-ft sheets in 0.125-in and 0.250-in thicknesses. All required samples for laminating and ballistics testing were cut from these sheets.

2. PU: A new family of PU materials was developed by Simula Technologies Inc.[++5] and marketed by Simula Polymer Systems Inc.[++] Two of these materials were of interest, Sim 2003 and Sim 1802. The Sim 2003 is a thermoset plastic that can be processed via casting or liquid injection molding. This material is clear with a very light straw tint and demonstrates very good impact resistance, even in thick sections. The Sim 2003 was considered as a replacement for PC for the riot visor and as the backing ply in the all-plastic and glass/plastic laminated systems. The material was purchased in 12-in × 12-in sheets in thicknesses of 0.125-in, 0.250-in, 0.375-in and, 0.50-in. The Sim 1802 is also a clear thermoset plastic with a light straw tint and is processed in the same manner as the Sim 2003, but it is much harder and consequently more brittle. The material was purchased in 12-in × 12-in × 0.125-in sheets. This material would be considered for use as the hardface in the all-plastic laminated systems.

[+] G E Plastics, One Plastics Ave., Pittsfield, MA 01201.
[++] Simula Technologies Inc, and Simula Polymer Systems Inc., 10016 S. 51st St., Phoenix, AZ 85044.

Glass and Glass/Ceramics

Three types of glass and one glass/ceramic were investigated:

1. Soda lime glass: Soda lime, or window glass, is widely used in transparent armor applications for both fragment and small arms protection. As such, it would be used as the baseline hardface for the glass/plastic laminated systems. It was purchased locally in 12-in × 12-in × 0.125-in plates and cut into 2-in × 2-in squares for ballistic laminate fabrication.

2. Vycor:* Vycor is a 96% fused silica glass which is a water-clear, high-strength glass that has shown promise as an armor material and was considered because of its low specific gravity. It was purchased in 2-in × 2-in squares, 0.125-in and 0.1875-in thick.

3. Fused silica: 100% fused silica is very similar to the Vycor. It was purchased in 2-in × 2-in squares, 0.125-in and 0.1875-in thick.

4. Transarm:** This material is a recrystallized lithium disilicate glass. It has all the workability of an amophorous glass, but once it has been crystallized, it demonstrates properties more like those of a ceramic. It was purchased in 2-in × 2-in squares, 0.125-in and 0.250-in thick. The 0.250-in samples were ground to 0.1875-in to maintain continuity of testing.

Interlayer

The interlayer used for all laminates was KPUR 300, a thermoplastic PU adhesive sold by KSH Inc., at the time of its purchase. This material is now sold by Morton Chemical Inc.# It is 0.050-in thick sheet material that can be layered to build up a required thickness.

SAMPLE FABRICATION

Plastic

Samples for ballistic testing were cut from the larger sheets. All the plastic samples were 6-in × 6-in.

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* Corning Inc., One Riverfront Plaza, Corning, NY 14831.

** Alstom UK Ltd., Research & Technology Centre Stafford, Staffordshire, ST17 4LN, England.

\# Morton International Inc., 100 N. Riverside Plaza, Chicago, IL 60606.

Plastic/Plastic

As with the monolithic plastic ballistic samples, the plastic/plastic samples were 6-in × 6-in. Prior to the lay-up procedure, all the plastic sheets and interlayers were cleaned thoroughly with isopropyl alcohol and allowed to air dry. The lay-up sequence was as follows: 1) 0.125-in sheet of the Sim 2003 was put down as the trailing ply, 2) a 0.050-in sheet of the PU adhesive interlayer was placed down, and 3) the 0.125-in Sim 1802 striking ply was then put down. Steps 2 and 3 were then repeated until the required sample thickness was achieved.

Glass/Plastic

Prior to the to the lay-up procedure, all glass-striking plies were cleaned thoroughly with acetone and then with isopropyl alcohol and allowed to air dry. All plastic sheets and interlayers were cleaned thoroughly with isopropyl alcohol and allowed to air dry. The lay-up sequence was then as follows: 1) a 12-in × 12-in sheet of either PU or PC was put down as the trailing ply, 2) two layers of the 0.050-in PU adhesive interlayer, cut to 2.125-in × 2.125-in, were then put down, and 3) a 2-in × 2-in glass-striking ply was then put down on top of the interlayer. Steps 2 and 3 were repeated until nine of the 2-in × 2-in lay-ups were arranged in an equally spaced 3 × 3 array on the striking ply (see Fig. 3).

Once the lay-up was completed, it had to bagged for autoclave processing. The bagging procedure was as follows: 1) the lay-up was wrapped in two layers of perforated peel ply, 2) the lay-up was then wrapped in two layers of 16-oz felt breather, 3) two vacuum glands were then placed on a piece of felt breather extending off the lay-up proper, and 4) the completed lay-up was then placed in a nylon bag. The bag was then sealed, and a vacuum was applied (Fig. 4).

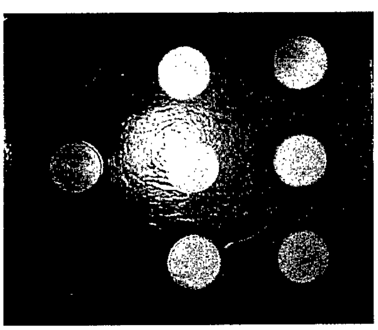

Fig. 3 Glass/Plastic Lay-up Array

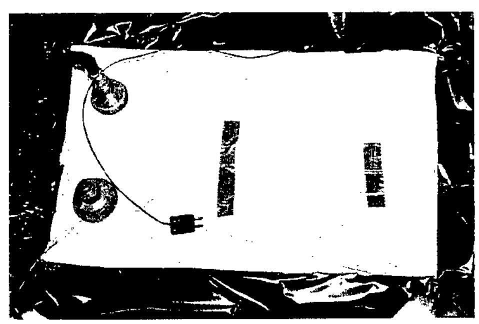

Fig. 4 Glass/Plastic Lay-up Bagged for Autoclave Bonding

Processing

A 3-ft × 6-ft microprocessor controlled autoclave was used to fabricate the plastic/plastic and glass/plastic laminates. The autoclave was capable of a maximum temperature of 800°F and a maximum pressure of 350 psi. The processing cycle used to bond the laminates required a maximum temperature of 200°F. A pressure of 75 psi was required for the glass/plastic laminates. This compressed the interlayer from 0.100 in down to approximately 0.080 in. A pressure of 150 psi was needed for the plastic/plastic laminates. This compressed the interlayer down from a starting thickness of 0.050 in to approximately 0.025 in. The total cycle time was 4 hours. Almost half of this time was devoted to an extremely slow cool down (1°F/min). This cooling rate was required to prevent cracking of the glass striking plies and warping of the all-plastic laminates.

EXPERIMENTAL

Ballistic Testing

Ballistic testing was carried out using a standard .22-caliber FSP weighing 1.1 grams. For velocities below 2000 ft/sec, the projectiles were fired from a 48-in-long gas gun connected to a high-speed solenoid valve leading to a helium gas cylinder. Before firing, a pressure was selected; the gun was fired by manual closure of an electrical circuit that opened the solenoid valve. The projectile velocities were determined by a pair of printed silver grid paper screens located in front of the specimen and connected to an electronic chronograph for time-of-flight measurements.[6]

For velocities above 2000 ft/sec, the testing was conducted using a 22-in-long, .223 barrel with a 1:12 twist. Projectile velocity was controlled by varying the amount of smokeless powder that was loaded into the brass case. The muzzle of the gun was placed 87 inches from the target fixture. An orthogonal flash radiograph system was used to measure projectile velocity, vertical pitch, and horizontal yaw. This system was initiated by a breakscreen placed 51 inches from the muzzle of the gun.

The ballistic test samples were clamped to a steel frame with four C-clamps, one at each corner. A 0.002-in aluminum witness foil was positioned 2 inches behind and parallel to the sample. V_{50} tests were conducted in accordance with MIL- STD-662.[7]

RESULTS AND DISCUSSION

Plastics

The results of the ballistic testing of the monolithic plastic materials are shown in Fig. 5. The data for acrylic[1] (PMMA) are included for comparison purposes only. The Sim 2003 PU demonstrated substantially better performance than the PC at every areal density tested. Areal density is defined as the weight per unit area. It should be noted that as areal density of the PU and the PC increased the performance of the PU relative to the PC increased. On average, the PU was about 30 - 35% better than the PC.

By looking at the data specifically for materials with thicknesses that could be used for the riot visor (Table 2), it is apparent that by simply substituting 0.250-in PU for the 0.250-in PC, a substantial gain in performance of 33% can be achieved. If one wanted to maintain the existing level of protection that the 0.250-in PC offers, the 0.125-in PU could be substituted. This would result in a 50% reduction in weight of the visor.

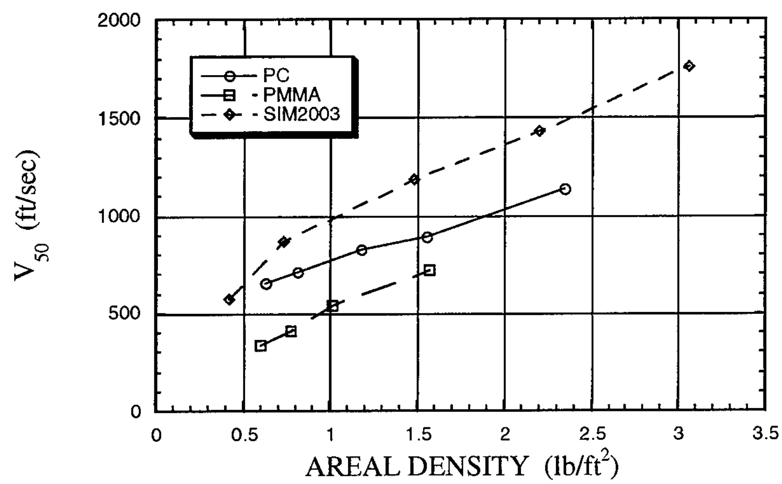

Fig. 5 Results of the Ballistic Testing of the Monolithic Plastic Materials

Table 2
RESULTS OF THE BALLISTIC TESTING OF THE RIOT VISOR MATERIAL

	V50 velocity w/ 17 grain ft/sec.- m/sec.	Approximate Areal Density lb/ft^2	Construction inches
PC	714/218	.813	0.125
PC	888/271	1.55	250
Sim 2003	864/263	.729	0.125
Sim 2003	1188/362	1.48	0.250

Laminates

The glass/plastic and, to a lesser extent, plastic/plastic laminates make use of the harder front-face material to deform the fragment. Crack formation is the energy absorption mechanism used to defeat the projectile. The trailing ply is typically a tougher material that will deform but not crack. Its role is to keep the spall and projectile away from the wearer. The glass/plastic laminates have a 0.080-in thick interlayer to accommodate the order of magnitude difference in coefficients of thermal expansion between the glass and plastic. The thicker interlayer is also needed to isolate the glass from the plastic and stop any cracks from propagating from the glass to the plastic. The plastic/plastic laminates require a much thinner, 0.010 - 0.015-in interlayer since the thermal expansion coefficients of the plastics are similar. The crack propagation problems are not as severe.

Plastic/Plastic Laminates Several different constructions of plastic/plastic laminates were evaluated (Table 3). All were fabricated using the Simula PU materials. The laminate construction that proved to be the most efficient is the second one listed in Table 3. It consists of three plies of the Sim 1802 and one ply of the Sim 2003. One 0.050-in thick sheet of interlayer is inserted between each PU ply to bond the laminate together. The 0.050-in thick interlayer was used because the 0.015-in thick material was not available. This nonoptimized laminate performed nearly as well as the glass/plastic systems, with only a slightly greater areal density. If the optimal thickness interlayer was used, the areal density would be very similar to that of the better performing glass/plastic systems. This optimized plastic/plastic laminate is also shown in Table 3. The plastic striking plies were not hard enough to deform the FSP.

Table 3
RESULTS OF THE BALLISTIC TESTING OF THE POLYURETHANE LAMINATES

	V50 velocity w/ 17 grain ft/sec.- m/sec.	Approximate Areal Density lb/ft^2	Construction out to in inches
PU Laminate	1995/608	4.25	0.125 Sim 2003/0.250 Sim 1802 /0.125 Sim 2003
PU Laminate	2021/616	3.84	0.375 Sim 1802/0.125 Sim 2003
PU Laminate	2510/765	5.2	0.125 Sim 1802/0.250 Sim 2003/ 0.125 Sim 1802
Optimized PU laminate	-	3.15-3.25	0.375 Sim 1802/0.125 Sim 2003

Glass/Plastics Laminates Two laminate constructions were evaluated. The first consisted of 0.125-in glass-striking ply laminated to a 0.250-in plastic-backing ply. This construction was chosen because it was the same as that used in a commercial glass/plastic visor. The second consisted of a 0.1875-in glass-striking ply laminated to a 0.125-in plastic-backing ply. This system was chosen because it is very close to the 2/3:1/3 ratio of hard face-to-trailing ply considered optimal for transparent armor used for small arms protection. In all cases, this second construction provided superior protection at a reduced areal density. The FSP was always deformed by the glass-striking ply.

Soda Lime Glass/Plastic The soda lime glass/PC and the soda lime glass/PU systems were use as baselines. Only the 0.125-in/0.250-in construction was used. The use of the

PU-striking ply improved the performance marginally. The results reported in Table 4 are fairly good. These would be the least expensive systems.

Table 4
RESULTS OF THE BALLISTIC TESTING OF THE SODA LIME GLASS/PLASTIC LAMINATES

	V50 velocity w/ 17 grain ft/sec.- m/sec.	Approximate Areal Density lb/ft^2	Construction out to in inches
SL glass/PC	2001/610	3.67	0.125/0.080/0.217
SL glass/ Sim 2003	2077/633	3.60	0.125/0.080/0.250

Vycor/Plastic Vycor/PC and Vycor/ PU laminates were fabricated in both laminate constructions. The 0.125-in/0.250-in Vycor /PC laminate was the only glass/plastic system that did not achieve a 2000 ft/sec V_{50} (Table 5). All other Vycor systems performed better that the Army PS820 system. In all cases, the PU-backed systems were better than the PC-backed systems. The Vycor systems also had the lowest areal densities of any glass/plastic systems tested.

Table 5
RESULTS OF THE BALLISTIC TESTING OF THE VYCOR LAMINATES

	V50 velocity w/ 17 grain ft/sec.- m/sec.	Approximate Areal Density lb/ft^2	Construction out to in inches
Vycor/PC	1962/598	3.14	0.121/0.080/0.217
Vycor/PC	2178/664	2.99	0.1875/0.080/0.125
Vycor/Sim 2003	2172/662	3.06	0.121/0.080/0.217
Vycor/Sim 2003	2261/689	2.97	0.1875/0.080/0.125

Fused Silica/Plastic Due to a limited supply of 0.1875 in fused silica, only the baseline fused silica/PC laminates were fabricated. Overall, the fused silica systems performed the best, providing the highest level of protection at areal densities comparable to those of the Vycor systems. The results are shown in Table 6.

Table 6
RESULTS OF THE BALLISTIC TESTING OF THE FUSED SILICA LAMINATES

	V50 velocity w/ 17 grain ft/sec.-m/sec.	Approximate Areal Density lb/ft^2	Construction out to in inches
Fused silica/PC	2097/639	3.14	0.121/0.080/0.217
Fused silica/ Sim 2003	2244/684	3.17	0.121/0.080/0.250
Fused silica/ Sim 2003	2484/757	2.98	0.1875/0.080/0.125

Transarm/Plastic Only the Transarm/PU systems were fabricated. Again, this was due to an extremely limited supply of the Transarm striking plies. These were the second best performing systems (see Table 7), but were as heavy as the soda lime glass/plastic baseline system.

Table 7
RESULTS OF THE BALLISTIC TESTING OF THE TRANSARM LAMINATES

	V50 velocity w/ 17 grain ft/sec.- m/sec.	Approximate Areal Density lb/ft^2	Construction out to in inches
Transarm/ Sim2003	2362/720	3.59	0.125/0.080/0.250
Transarm/ Sim2003	2379/725	3.31	0.1875/0.080/0.125

CONCLUSIONS

The results of the ballistic testing show that the Sim2003 PU material is substantially better than PC for low velocity fragment protection, and that this increased level of protection is maintained even at thicknesses above 0.125 in. This is a viable material for the riot visor and other military eye protection devices such as SWD goggles, aircrew visors, and spectacles. Results of the ballistic testing of the PU laminates indicate that these materials do provide the level of protection required for EOD and mine clearing operations. The design of these laminates must be optimized to achieve the predicted weight savings. Further work is also required to fully characterize the environmental durability of these materials.

Glass/plastic laminates also show promise for high-velocity fragment protection. This is true particularly for the high-temperature glasses and glass/ceramics. Laminates made with these materials have demonstrated the highest levels of protection at the lowest areal densities. The glass/ceramics can be formed like plate glass. However before high-temperature glasses such as fused silica can be used for visor applications, the processing and economic issues associated with forming these materials must be overcome.

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13. ABSTRACT*(Maximum 200 words)*

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